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13. ABSTRACT (Maximum 200 words)

Progress under AFOSR Contract F49620-92-C-0004 for the period 15 October 1991to 31 October 1992 is reported. Important results include studies of the grain boundaries in a-axis oriented high-Tc superconducting 123 YBCO thin films, the study of the vortex properties of high-Tc single crystals of the superconductor 2212 BSCCO and the artificially structured Mo-Ge/Ge quasi-two-dimensional superconductors. The latter provide an outstanding model system for the study of vortices in highly anisotropic superconductors, such at the high-Tc cuprates, without all the attendant difficult materials problems. Progress in the synthesis and study of the so-called infinite layer cuprate $SrCuO_4$ and the normally conducting oxide $SrRuO_3$ of interest as a barrier materials in high-Tc SNS devices are also reported. Finally we report the development of advanced approaches to rate control of the cation fluxes in the reactive coevaporation of the high-Tc superconductors.

14. SUBJECT TERMS
High-Tc superconductivity, anisotropic superconductivity, $SrCuO_4$, $SrRu)_3$, Mo-Ge/Ge superconducting multilayers.

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ADVANCED THIN-FILM DEPOSITION & PHYSICAL PROPERTIES OF HIGH-TEMPERATURE & OTHER NOVEL SUPERCONDUCTING MATERIALS

Principal Investigators
M. R. Beasley, T. H. Geballe, and A. Kapitulnik

Annual Technical Report
under
AFOSR Contract F49620-92-C-0004
for the period 15 October 1991–31 October 1992

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Annual Report
AFOSR Contract F49620-92-C-0004
Stanford University

M. R. Beasley, A. Kapitulnik and T. H. Geballe

Period from October 15, 1991 to October 14, 1992

I. Research Accomplishments

We have investigated the structure and properties of well-defined model grain boundaries, being motivated by the fact that grain boundaries are important in Josephson junctions and in high-field high-current conductors.

The transport properties of three types of 90-degree grain boundaries were compared using (103) oriented $YBa_2Cu_3O_7$ (YBCO) thin films grown epitaxially on (101) $SrTiO_3$ and (101) $LaAlO_3$ substrates. The three types of grain boundaries that arise in such films are shown in Fig. 1. The films were grown using the *in situ* 90-degree off-axis sputtering approach developed earlier by our group . The in-plane crystallographic film orientation is given by the YBCO <301> parallel to the substrate [101]. A domain structure exists with the CuO_2 planes oriented at $\pm$ 45 degrees to the substrate surface (i.e., parallel to the substrate [010] direction). Specific sets of 90 degree grain boundaries are observed in both principal in-plane directions. The normal-state conductivity and the critical current density of these films along the YBCO [010] direction are as high as the best quality c-axis films, which have no high-angle grain boundaries. This demonstrates that twist boundaries (Type A in Fig. 1) have no discernable weak link nature. The normal-state conductivity and critical current density along the <301> direction are much lower than in the [010] direction. The normalized magnetic-field dependence of J_c for both those directions is similar and shows no evidence of weak link behavior. The anisotropic transport behavior in the normal and superconducting state can be explained by the microstructure and a simple transport model.

A-axis-oriented $YBa_2Cu_3O_7$/$PrBa_2Cu_3O_7$ superlattices and their transport properties have been grown with smooth surface and high crystalline quality. The materials can be visualized as a parallel array of narrow 1-D-like channels of the copper oxide planes of YBCO separated by the PBCO layers. The magnetic field dependence of the resistive transitions of superlattices containing individual $YBa_2Cu_3O_7$ layers 24 or 48 Å thick separated by $PrBa_2Cu_3O_7$ layers 24 or 48 Å thick shows an apparent dimensional cross-over at a temperature T* that depends on the

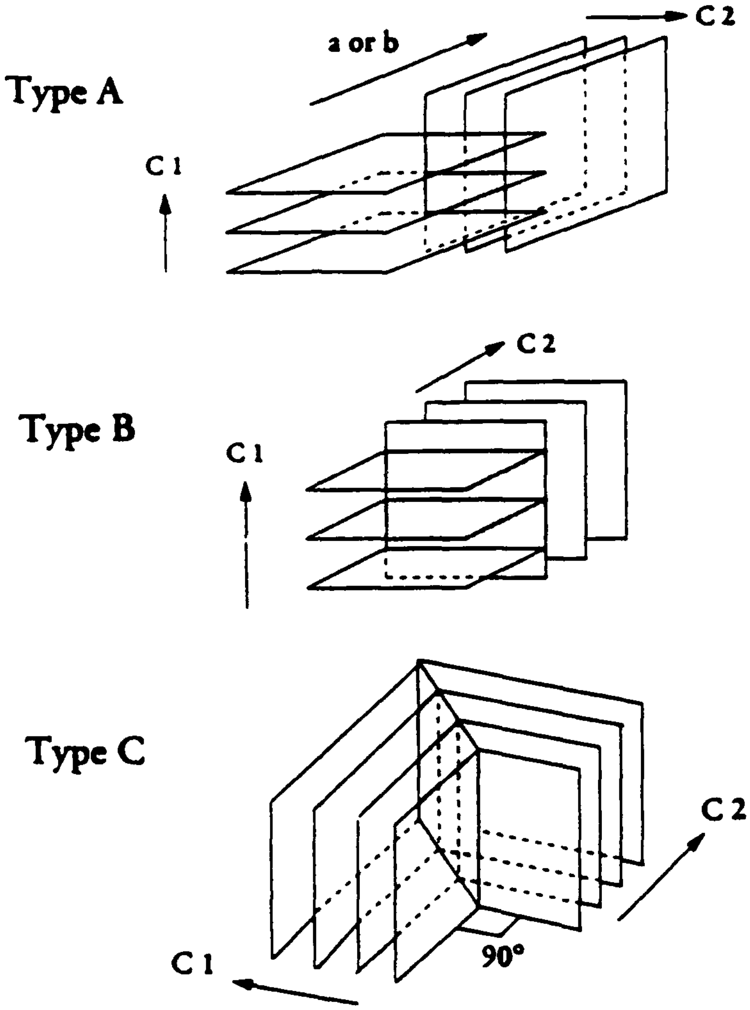

Fig. 1. Schematic diagrams of various 90° grain boundaries that arise in 103 oriented YBCO film; a 90° [010] twist boundary (type A), a 90° [010] basal-plane-faced tilt boundary (type B), and a 90° [010] symmetrical tilt boundary (type C). Note that a 90° [001] tilt boundary is a (110) twin boundary.

$PrBa_2Cu_3O_7$ thickness. Above T* the transition is insensitive to magnetic fields (up to 8 T); below T* some broadening occurs. These results indicate an abrupt disappearance of the coupling between the $YBa_2Cu_3O_7$ channels in the structure above T*.

An universal feature of the high-Tc cuprate superconductors is their strong anisotropy. This anisotropy fundamentally affects the properties of these superconductors in the vortex state. We are studying the effects of such anisotropy both by studying the cuprates directly (such as in the a-axis YBCO/PbCO multilayers described above) and by using a novel model system based on the artificially-structured MoGe/Ge superconductor/insulator multilayer system with anisotropies that can be adjusted to match those of high-Tc superconductors. We also are studying for comparison the behavior of individual layers, an approach that is not yet possible in the high-Tc materials.

More specifically, we have studied the defect dependence of the irreversibility line in $Bi_2Sr_2CaCu_2O_8$ for magnetic fields along the c-axis. We find that the irreversibility line of pristine single crystals exhibit three regimes. For fields less than 0.1 T, it obeys a power law, $H_{irr} = H_0(1-T_{irr}/T_c)^{\mu}$, where μ and H_0 are functions of T_c. For fields greater than 2 T, the irreversibility line becomes roughly linear ($\mu = 1$) with a slope of 0.7 T/K. For *intermediate* fields, there is a crossover region, which corresponds to the onset of collective vortex behavior. Defects produced by proton irradiation shift the irreversibility line in all three regimes. The high-field regime moves to higher temperatures, the low-field regime moves to lower temperatures, and the crossover to collective behavior becomes obscured. A maximal increase in the irreversibility temperature in the high-field regime is found to occur at a defect density of nearly one defect per vortex disk. These results demonstrate that the high-field current carrying capacity of 2212 BSCCO, which is limited by the position of the irreversibility line, can be increased by the introduction of appropriate (columnar) defects.

We have also used measurements of the ac penetration depth of amorphous MoGe multilayers and single films in the presence of a perpendicular magnetic field to study the nature of the correlations of the vortex lattice of highly anisotropic and two-dimensional superconductors. The results reveal an anomaly in the ac response of the vortex lattice at a characteristic temperature below the $H_{c2}(T)$ line. We have found that the field and frequency dependence of this anomaly is consistent with a Kosterlitz-Thouless type melting of the two-dimensional vortex lattice on short length scales. However, we observe a crossover in the frequency dependence which suggests that even below the melting temperature the vortex lattice remains disordered on long length scales. This is in fact the first direct and unambiguous observation of a Kosterlitz-Thouless type melting of the vortex lattice in any kind of superconductor. Moreover, it confirms the suspicion that many previous claimed observations (in particular those for high-Tc superconductors) were of electromagnetic origin (i.e., skin-depth effects) and not actually indicative of melting.

Using our thin Mo-Ge films we have also studied the resistive transition of two-dimensional superconductors (i.e., single layers) in a magnetic field. Activation energies for vortex motion as a function of magnetic field have been deduced from the data. Study of the systematics of these data convincingly shows that at low fields an edge barrier to vortex entry governs the resistance. The relevance of this effect for superconducting flux flow transistors will be interesting to examine. At higher fields and for the thinnest films, we find that the activation energy decreases logarithmically with increasing magnetic field. This same behavior has been reported in c-axis YBCO/PBCO multilayers. Thus we believe we are examining the same vortex dynamics as arises in the high-Tc materials. The data are consistent with recent theories which predict that at high J_c the activation energy for flux motion is governed by motion of dislocations in the vortex lattice. For thicker films, which have lower critical current densities, a non-monotonic field dependence is seen that empirically correlates with the theoretical field dependence expected for vortex motion in the form of correlated "flux bundles" with a diameter given by the Larkin-Ochinokov correlation length. Thus both of these behaviors arise for film thicknesses less than those for which the vortex melting was observed. The precise connection between these two regimes needs to be elucidated but clearly reflects the lower critical current densities of the thicker films.

Working with Intelligent Sensor Technology Inc, a small instrumentation company in Silicon Valley, we have developed a new approach to atomic absorption rate control that defines the state of the art. We have achieved 1% noise at a deposition rate of 0.3 Å/sec with a control bandwidth suitable for atomic layer-by-layer growth using electron beam heated sources. This has been achieved in the high background pressures of activated oxygen needed for growth of the cuprate superconductors. The approach appears to have potential utility for sputtering processes used in semiconductor manufacturing.

Using our MBS system we have deposited thin films of the so-called infinite layer material $SrCuO_2$ and the normally conducting perovskite $SrRuO_3$ that has shown potential as a normal barrier materials in high-Tc SNS Josephson devices. Preliminary doping studies of the infinite layer material have been undertaken. *In situ* UPS studies of the ruthenate show a very large density of states at the Fermi level, raising interesting questions about the origin of the high resistivity of this material.

Under the AASERT supported part of our program, we have explored the materials science and electronic structure of the Sr doped fullerene

Sr_xC_{60}, with x = 0.2 to 6. Unlike previous workers, we are doping the material using codeposition, as opposed to post-deposition diffusion of the dopant in from the surface. In principle our approach should lead to more uniform doping. The fullerene source is a temperature stabilized Knudsen cell, and the Sr dopant was deposited using an electron beam heated source and atomic absorption rate control. Preliminary evidence shows differences in the valance band photoemission spectra from our codeposited films and those reported in the literature doped via diffusion. These possible differences are under continuing investigation.

II. List of Publications

1. "Defect dependence of the irreversibility line in $Bi_2Sr_2CaCu_2O_8$ single crystals," by L.W. Lombardo, D.B. Mitzi, A. Kapitulnik, and A. Leone, Phys. Rev. B **46**, 5615 (1992).

2. "Vertical Transport Properties of a-Axis Oriented YBa_2Cu_3O/ $PrBa_2Cu_3O_7$ $YBa_2Cu_3O_7$ Sandwich Junctions," Debra Lew, Yuri Suzuki, C. B. Eom, M. Lee, J.-M. Triscone, T. H. Geballe, and M. R. Beasley, Physica C, **185-189** (1991) pp. 2553-2554 (North Holland.)

3. "Tunneling and Proximity Effect Studies of the High Temperature Superconductors," M.R. Beasley, Physica C **185-189** (1991) pp. 227-233 (North Holland).

4. "Two-Dimensional Superconductivity in Ultrathin Disordered Thin Films," M.R. Beasley, Helvetica Physica Acta **65**, 187-196 (1992).

5. "Vortices in Artificially-Structured Quasi Two-Dimensional Superconductors," M.R. Beasley, W.R. White, M. Hahn, and A. Kapitulnik, Physica Scripta, **T42**, 25-28, 1992. (Invited paper, presented at Jubilee Nobel Symposium, December 4-7, 1991, Goteborg, Sweden.)

6. "Specific Heat of a Superconducting Multilayer: 2D Fluctuations and 2D-0D Crossover," J.S. Urbach, W.R. White, M.R. Beasley, and A. Kapitulnik, Phys. Rev. Lett. **69**, 2407-2410 (Oct. 1992).

III. List of Visitors

Short Term Visitors

Dr. K. Nakamura	National Inst. of Metals	Nov. 11–24, 1991
M. Kupriyanov	Moscow State Univ.	Jan. 2-5, 1992
Dr. Imafuku	Nippon Steel Corp.	April 16, 1992
Dr. Ray Ashoori	AT&T	April 22, 1992
Dr. Hans Mooij	Delft	April 26–27, 1992
Dr. David Nelson	Harvard University	April 28, 1992
Dr. Gun Yong Song	ETRI	May 4, 1992
Ken Daley	TRW	Sept. 17, 1992
Alfred Lee	TRW	Sept. 17, 1992
Claire Pittiet-Hall	TRW	Sept. 17, 1992

Long Term Visitors

Toshimasa Umezawa	Yokogawa Electric Co.	June 1991–Dec. 1992
Alberto Pomar	Universidad de Santiago	Jan. 1992–Feb. 1992
Dr. Guntherodt	Univ. Basel, Switzerland	July 1–Aug. 16, 1992
John Clem	Iowa State University	Sept. 1992–July 1993
Roland Busch	Siemens AG	Oct.–Dec. 1992
Zafer Durusoy	Hacettepe University	Oct. 92–May 1993

IV. Graduate Students Completing Ph.Ds

Steven Spielman	Lawrence Berkeley Labs Berkeley, Calif.	1992